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(54) **MULTI-LAYER ADVANCED CARBON NANOTUBE BLACKBODY FOR COMPACT, LIGHTWEIGHT, AND ON-DEMAND INFRARED CALIBRATION**

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(51) **Int. Cl.**

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G01J 5/52	(2006.01)
H01L 51/00	(2006.01)
H01L 29/06	(2006.01)

(52) **U.S. Cl.**

CPC ***G01J 5/522*** (2013.01); *H01L 29/0673* (2013.01); *H01L 51/0048* (2013.01); *Y10S 977/949* (2013.01)

(58) **Field of Classification Search**

CPC G01J 5/522; G01J 5/023; H01L 27/14; H01L 29/06

See application file for complete search history.

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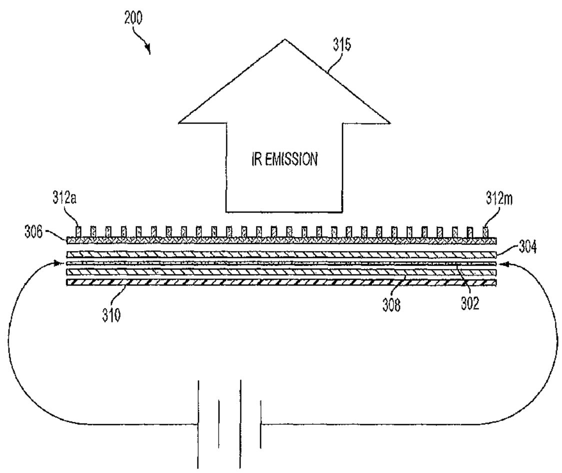
(57) **ABSTRACT**

An apparatus, method and thin-film structure for producing a blackbody spectrum is disclosed. A first layer of the apparatus is configured to generate heat in response to an applied voltage. A second layer is configured to emit the blackbody radiation spectrum in response to the heat from the first layer. A thermal spreading layer is disposed between the first layer and the second layer. The thermal spreading layer includes a graphene sheet for reducing a spatial variation of the heat in a plane of the thermal spreading layer.

20 Claims, 6 Drawing Sheets



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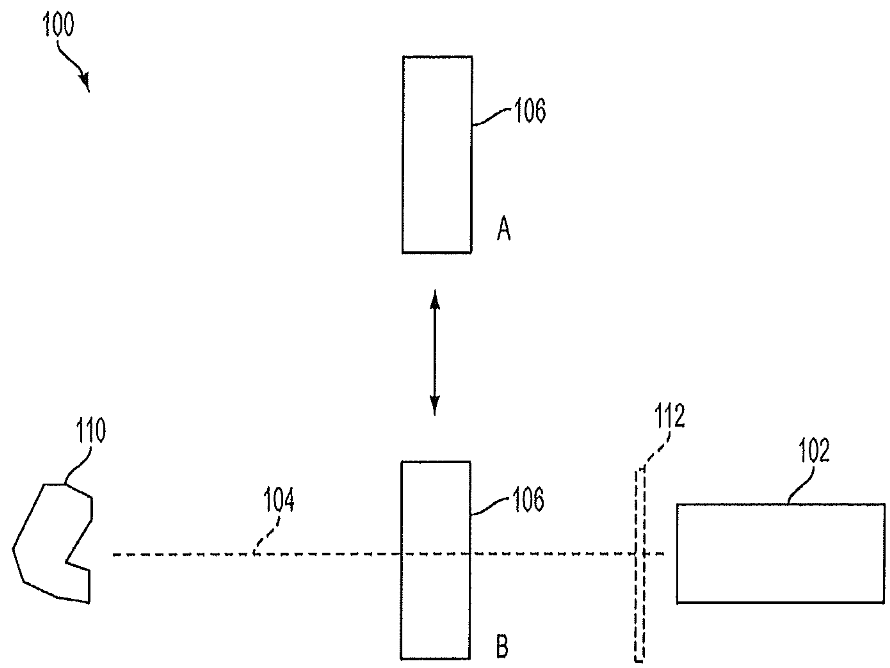

FIG. 1

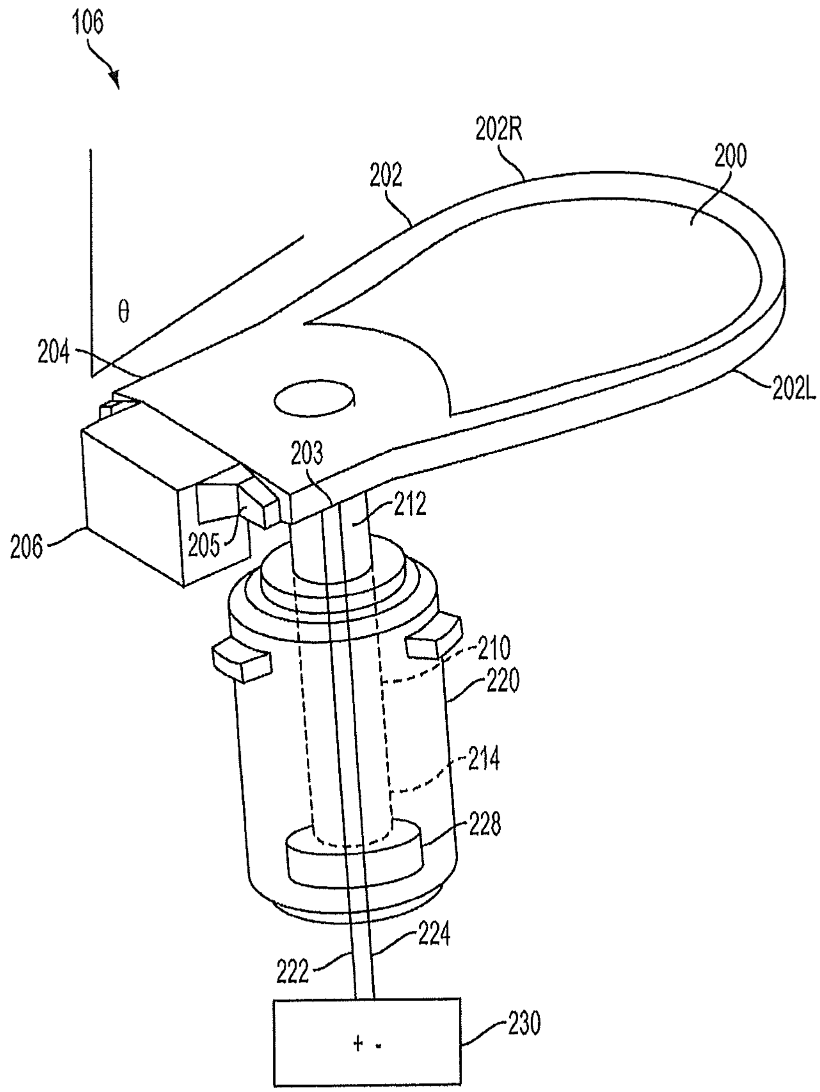
106
202R
200
202
θ
204
202L
203
212
206
205
210
220
214
228
224
222
230
+ -

FIG. 2

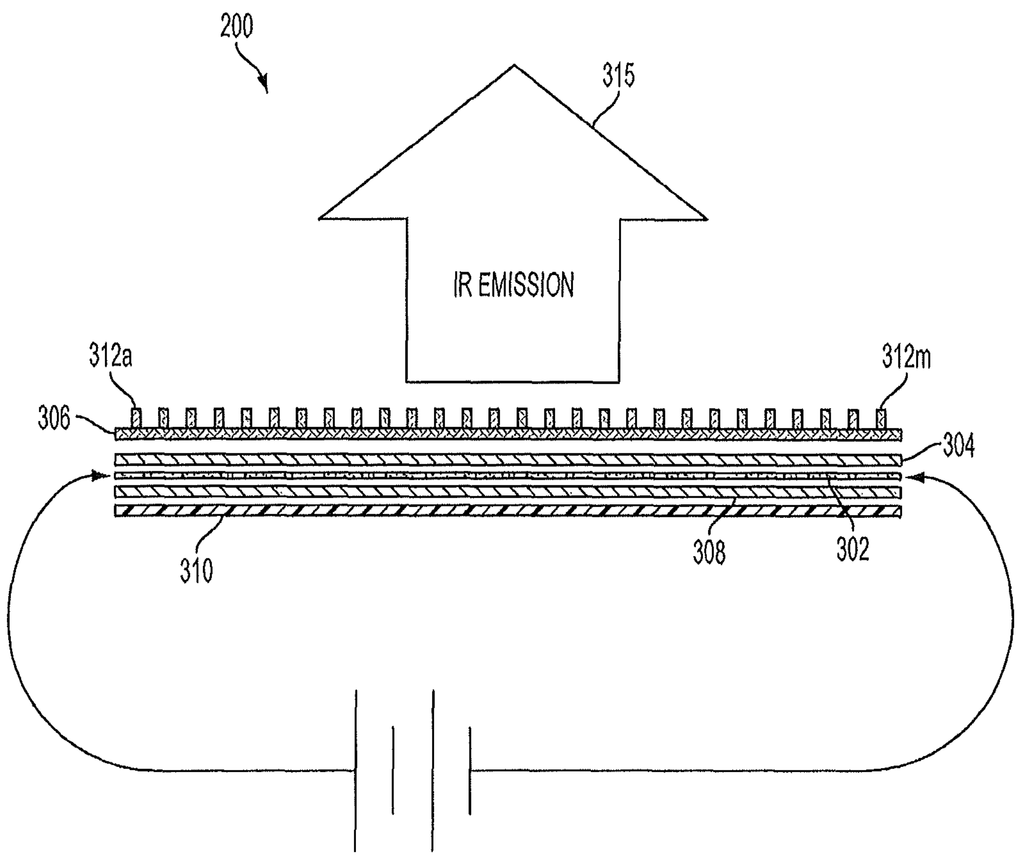

FIG. 3

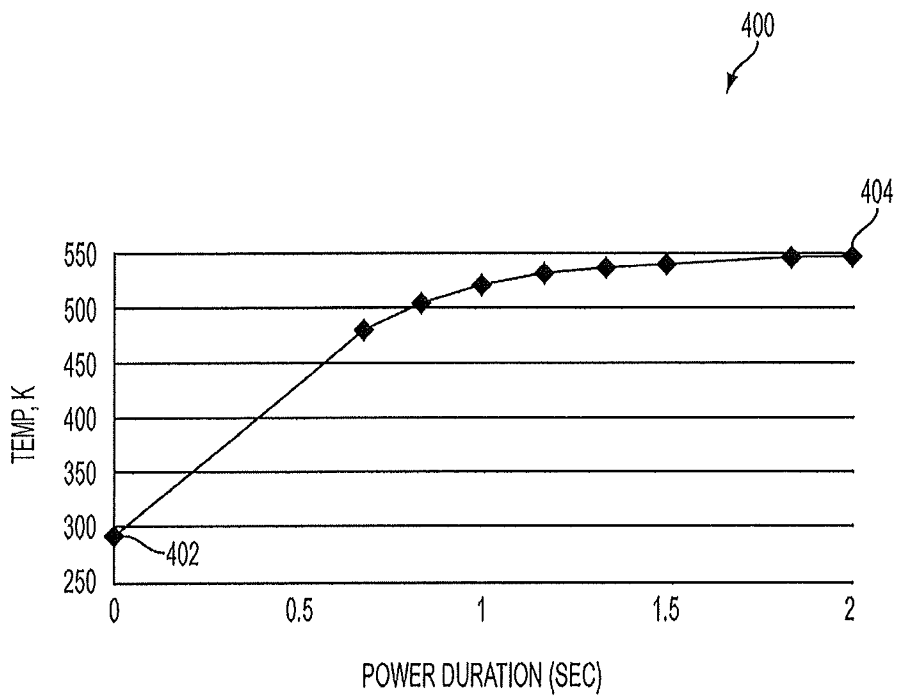
400
404
550
500
450
400
350
300
250
TEMP, K
402
0
0.5
1
1.5
2
POWER DURATION (SEC)

FIG. 4

CONSTANT CURRENT (A)	TARGET TEMP(K)	MEASURED TEMPERATURES (KELVIN)		
		10 SEC	60 SEC	180 SEC
1	300	306 ± 1	307 ± 1	307 ± 1
3	353	348 ± 6	351 ± 3	351 ± 2
5	433	435 ± 7	435 ± 7	439 ± 4
8	515	526 ± 5	525 ± 7	525 ± 5

FIG. 5

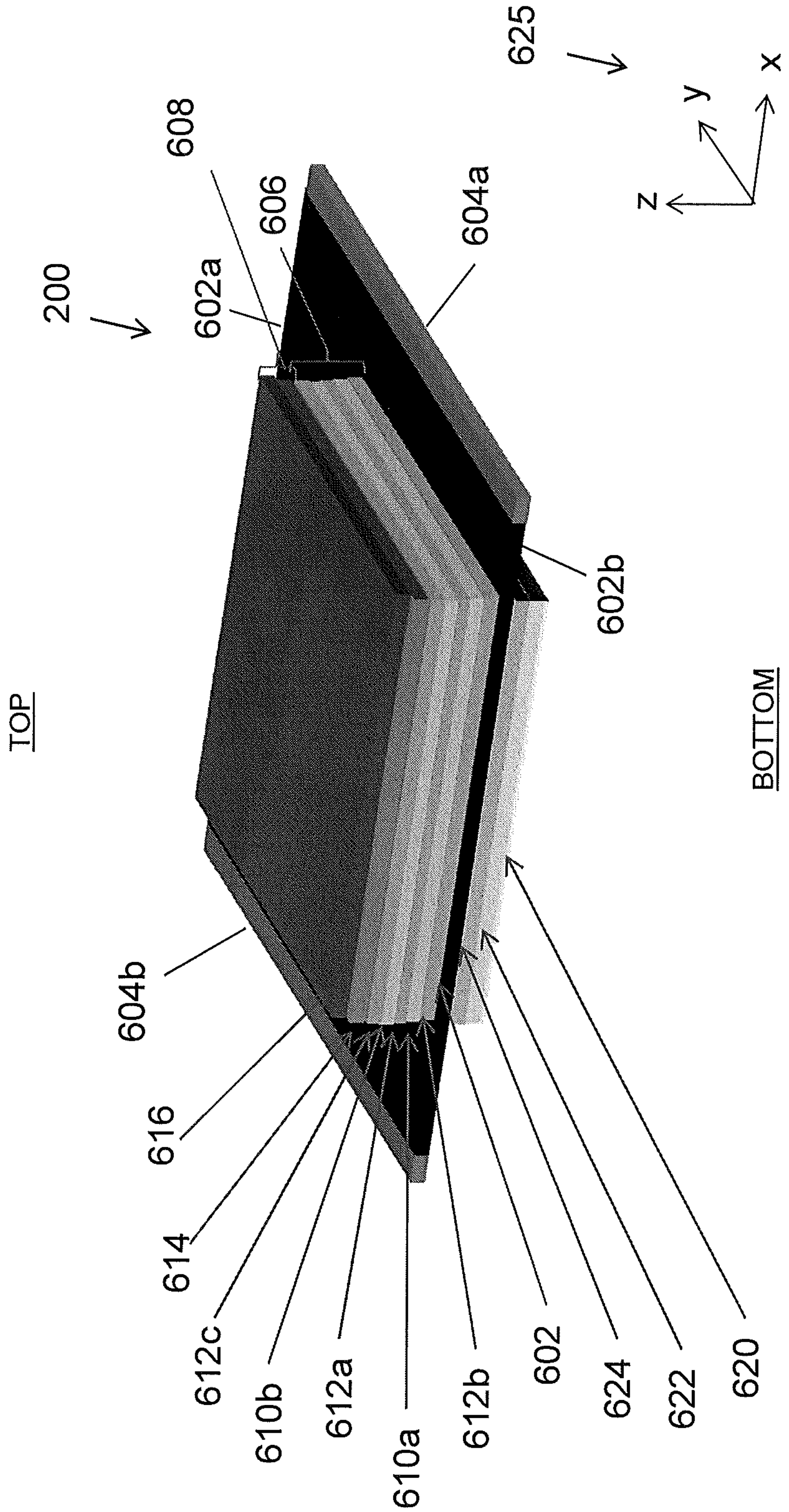
TOP
BOTTOM
200
625
x
y
z
608
606
602a
604a
602b
604b
616
614
612c
610b
612a
610a
612b
602
624
622
620

Figure 6

MULTI-LAYER ADVANCED CARBON NANOTUBE BLACKBODY FOR COMPACT, LIGHTWEIGHT, AND ON-DEMAND INFRARED CALIBRATION

CROSS REFERENCE TO RELATED APPLICATIONS

The present application is a continuation-in-part of U.S. application Ser. No. 13/894,953, filed on May 15, 2013.

BACKGROUND

The present disclosure relates to generating a radiation spectrum and, in particular, to a method and apparatus for generating blackbody radiation spectra.

In various optical systems, an optical signal is received from an object at an optical sensor and measurements of the optical signal are obtained at the optical sensor to determine a property of the object. In order to obtain accurate measurements, it is often necessary to calibrate the optical sensor using a known photon flux at one or more standard wavelengths. One method for providing the photon flux at standard wavelengths includes heating one or more blackbody radiators to selected temperatures and using optical filters to select the calibration wavelength. However, the use of blackbody sources to calibrate an optical sensor introduces size, weight, and power (SWaP) challenges. First of all, a conventional blackbody radiator needs to be heated for a relatively long time prior to use in calibration in order to bring the blackbody radiator to the selected temperature and to maintain the selected temperature. Conventional blackbody sources therefore consume a large amount of power. Secondly, conventional blackbody sources and their supporting optical structures are generally bulky, and using one or more of them requires a precise optical mechanism to image each blackbody emission spectrum onto the sensor undergoing calibration. Third, such a blackbody radiator calibration system and its accompanying optical mechanisms are generally heavy and cumbersome.

SUMMARY

According to one embodiment of the present disclosure, an apparatus for producing a blackbody spectrum includes: a first layer configured to generate heat in response to an applied voltage; a second layer configured to emit the blackbody radiation spectrum in response to the heat from the first layer; and a thermal spreading layer between the first layer and the second layer, the thermal spreading layer including a graphene sheet for reducing a spatial variation of the heat in a plane of the thermal spreading layer.

According to another embodiment of the present disclosure, a film for generating a blackbody radiation spectrum includes: a first layer configured to generate heat in response to an applied voltage; a second layer configured to emit the blackbody radiation spectrum in response to the heat from the first layer; and a thermal spreading layer between the first carbon nanotube layer and the second carbon nanotube layer, the thermal spreading layer including a graphene sheet for reducing a spatial variation of the heat in a plane of the thermal spreading layer.

According to another embodiment of the present disclosure, a method of producing a blackbody radiation spectrum includes: applying a voltage to a first layer of a thin film device comprising the first layer, a second layer and at least one graphene sheet disposed between the first layer and the second layer in order to generate heat at the first layer; and using the at least one graphene sheet to reduce a spatial variation of the heat in the plane of the thin film device, wherein the heat having the reduced spatial variation excites photons at the second layer to produce the blackbody radiation spectrum.

Additional features and advantages are realized through the techniques of the present disclosure. Other embodiments and aspects of the disclosure are described in detail herein and are considered a part of the claimed disclosure. For a better understanding of the disclosure with the advantages and the features, refer to the description and to the drawings.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

The subject matter which is regarded as the disclosure is particularly pointed out and distinctly claimed in the claims at the conclusion of the specification. The forgoing and other features, and advantages of the disclosure are apparent from the following detailed description taken in conjunction with the accompanying drawings in which:

FIG. **1** shows an exemplary optical system for detecting light or an optical signal according to an exemplary embodiment;

FIG. **2** shows a detailed view of the exemplary calibration apparatus shown in FIG. **1**;

FIG. **3** shows a detailed view of the of the exemplary thin film structure of FIG. **2**;

FIG. **4** illustrates a response time for achieving an equilibrium temperature when applying a current to an exemplary carbon nanotube film of the present disclosure;

FIG. **5** shows a table illustrating a relation between current supplied to the exemplary carbon nanotube film of FIG. **4** and resulting spatial and temporal equilibrium temperatures of the carbon nanotube film; and

FIG. **6** shows a cross-sectional view of the thin film structure of the present disclosure in an alternate embodiment.

DETAILED DESCRIPTION

FIG. **1** shows an exemplary optical system **100** for detecting light or an optical signal according to an exemplary embodiment. The optical system **100** includes a sensor **102**, such as an optical sensor or optical detector. Light or optical signals propagating along the optical path **104** from a selected object or target **110** are detected at the sensor **102**. In order to maintain sensor accuracy, a calibration apparatus **106** ("calibrator") is moved into the optical path **104**. In an exemplary embodiment, the optical system **100** may operate in a sensing mode in which the calibration apparatus **106** is located at a first location A out of the optical path **104** of the optical sensor **102**. The optical system **100** may also operate in a calibration mode in which the calibration apparatus **106** is moved to a second location B in the optical path **104** of the optical sensor **102**. Once in the optical path **104**, the calibration apparatus **106** blocks light or optical signals from the object **110** from reaching the optical sensor **102**. The calibration apparatus **106** is then operated to provide light at one or more calibration wavelengths to the sensor **102** in order to calibrate the sensor **102**. A filter **112** is shown that is placed between the calibration apparatus **106** and the sensor **102** when the calibration apparatus **106** is at second location B. The filter **112** allows a photon flux within a selected wavelength window corresponding to a calibration wavelength to reach the sensor **102** in order to calibrate the sensor **102** to the calibration wavelength. In an exemplary embodiment, a wavelength window is from about 3 microns to about 5 microns.

FIG. **2** shows a detailed view of the exemplary calibration apparatus **106** shown in FIG. **1**. The exemplary calibration apparatus **106** includes a thin film structure **200** providing an extended surface area for emitting light or photons at a range of wavelengths. The thin film structure **200** may be bounded by a brace structure **202** that is coupled to the edges of the thin film structure **200**. In an exemplary embodiment, the brace structure **202** is configured to apply a slight outward force in the plane of the thin film structure **200** in order to maintain a substantially flat surface of the thin film structure **200**. Ends **203** and **204** of the brace structure **202** may be coupled or secured to a unit **206** via a securing device **205** such as a screw, bolt, etc. When secured to the unit **206**, the ends **203** and **204** are further coupled to an upper end **212** of a rod **210**. The rod **210** includes the upper end **212** for coupling to the thin film structure **200** via brace ends **203** and **204** and a lower end **214** extending within a housing **220**. The rod **210** is rotatable within the housing **220** and an actuator assembly **228** of the housing **220** is used to rotate the rod **210** and hence the thin film structure **200** through a selected angle θ. The calibration apparatus **106** may be oriented with respect to the sensor **102** such that rotation of the rod **210** through angle θ moves the thin film structure **200** from a first location (e.g., location A in FIG. **1**) to a second location (e.g., location B in FIG. **1**). Alternatively, the calibration apparatus **106** may be linearly displaced between the first location and the second location.

In various embodiments, wires **222** and **224** traverses an interior of the rod and/or housing to the brace structure **202**. Wire **222**, disposed along a right side **202**R of the brace structure **202**, provides an electrical coupling to one edge of the thin film structure **200**. Wire **224**, disposed along a left side **202**L of the brace structure **202**, provides an electrical coupling to an opposing edge of the thin film structure **200**. At a location distal to the brace structure **202**, the wires **222** and **224** are coupled to opposing poles of a controllable power supply **230**. Therefore, a current circuit is completed to provide current from the positive pole of the power supply **230** through wire **222** into the right side **202**R of the brace structure **202**, across the thin film structure **200** into wire **224** at the left side **202**L of the brace structure **202**, and into negative pole of the power supply **230**. Variable voltage is supplied to the thin film structure **200** via the controllable power supply **230**. In various aspects, applying a current to the thin film structure **200** raises a temperature of the thin film structure **200**. At a selected temperature, the thin film structure **200** generally emits photons having a characteristic blackbody radiation spectrum, wherein the blackbody radiation spectrum includes a characteristic wavelength indicating a peak emission of the spectrum and that is related to the temperature of the thin film structure **200**. In general, a total number of photons emitted by a blackbody radiator, as well as a number of photons emitted by the blackbody radiation within a selected range of wavelengths, are related to its temperature. As the temperature increases, the total photon flux and the photon flux within the selected wavelength range also increase. An operator may control the voltage or current at the controllable power supply **230** to cause a selected blackbody radiation spectrum to be emitted at the thin film structure **200**. A characteristic wavelength and other features of the radiation spectrum is related to the magnitude or amount of the applied voltage. A photon flux within the selected range of wavelengths may then be measured at the optical sensor **102** to calibrate the optical sensor **102**.

FIG. **3** shows a detailed view of the of the exemplary thin film structure **200** of FIG. **2**. In an exemplary embodiment, thin film structure **200** includes a first carbon nanotube layer **302**. The first carbon nanotube layer **302** includes a sheet of carbon nanotubes generally oriented to lie within the plane of the first carbon nanotube layer **302**. One end of the first carbon nanotube layer **302** is coupled to a positive pole of a controllable power supply **320** and an opposing end of the first carbon nanotube layer **302** is coupled to a negative pole of the controllable power supply **320** in order to complete an electrical circuit through the first carbon nanotube layer **302**. A first thermally conductive layer **304** is coupled to a top surface of the first carbon nanotube layer **302**, wherein the top surface is the surface of the first carbon nanotube layer **302** facing toward the IR emission arrow **315**. A second thermally conductive layer **308** is coupled to a bottom surface of the first carbon nanotube layer **302**, wherein the bottom surface is the surface of the first carbon nanotube layer **302** facing away from the IR emission arrow **315**. In various embodiments, the first and second thermally conductive layers **304** and **308** are made of an electrically insulating material such as a ceramic material. A second carbon nanotube layer **306** is coupled to the first thermally conductive layer **304** opposite the first carbon nanotube layer **302**. The second carbon nanotube layer **306** is configured to emit photons in a selected direction as indicated by IR emission arrow **315** in response to heat generated at the first carbon nanotube layer **302**. The second carbon nanotube layer **306** includes a plurality of carbon nanotubes **312***a*-**312***m* oriented so that the longitudinal axes of the plurality of carbon nanotubes **312***a*-**312***m* are substantially normal to the surface of the second carbon nanotube layer **306**. In general, photons excited at the second carbon nanotube layer **306** are emitted into the half-space above the second carbon nanotube layer **306** containing the indicative IR emission arrow **315**. Those photons that are emitted in the normal direction indicated by IR emission arrow **315** are used for calibration, as indicated by IR emission arrow **315**. In various embodiments, emissivity of the second carbon nanotube layer **306** is greater than about 0.995. A low emissivity metal film **310** is coupled to a surface of the second thermally conductive layer **308** opposite the first carbon nanotube layer **302**. In various embodiments, the low emissivity metal film **310** is configured to prevent heat from being radiated from the back end of the calibration apparatus thin film structure **200**.

To operate the exemplary thin film structure **200**, controllable power supply **320** supplies an electrical current to the first carbon nanotube layer **302** which generates heat in response to the supplied electrical current. The temperature and the amount of heat generated at the first carbon nanotube layer **302** are directly related to the amount of applied power. The first carbon nanotube layer **302** responds quickly to reach a selected equilibrium temperature when a current suitable for obtaining the equilibrium temperature is applied, as discussed below with respect to FIG. **4**. In an exemplary embodiment, the first carbon nanotube layer **302** reaches an equilibrium temperature within seconds of applying current to the first carbon nanotube layer **302**. The temperature at the surface of the first carbon nanotube layer **302** generally has a spatial variation described below with respect to FIG. **5**. The spatial variation is in a temperature range of a few Kelvin. The heat generated at the first carbon nanotube layer **302** is dispersed through first thermally conductive layer **304** to excite photons at a broad range of wavelengths at the second carbon nanotube layer **306**. The first thermally conductive layer **304** disperses heat generated at the first carbon nanotube layer **302** in the plane of the first thermally conductive layer **304**. Thus, any variations in temperature and heat generation at the first carbon nanotube layer **302** are substantially smoothed once the heat reaches the second carbon nanotube layer **306**. In various embodiments, the temperature at the second carbon nanotube layer **306** has a spatial variation of less than 1.0 Kelvin across the surface of the second carbon nanotube layer **306**. In another embodiment, the spatial variation is less than 0.5 Kelvin. In yet another embodiment, the spatial variation is less than 0.1 Kelvin. Thus, each of the plurality of carbon nanotubes **312***a*-**312***m* at the second carbon nanotube layer **306** receives substantially a same amount of heat from the first thermally conductive layer **304**. The heat received at the second carbon nanotube layer **306** excites photons which are directed along the longitudinal axis of the plurality of carbon nanotubes **312***a*-**312***m* and thus generally propagate along the direction indicated by IR emission arrow **315**. In addition, a flux of photons is also emitted in off-normal directions. The resulting spectrum from the second carbon nanotube layer **306** therefore is substantially equivalent to a blackbody radiation spectrum for a conventional blackbody heated to a substantially uniform temperature.

FIG. **4** illustrates a response time for achieving an equilibrium temperature at the first carbon nanotube layer **302** when applying a current to an exemplary carbon nanotube film **200** of the present disclosure. Temperature is plotted along the ordinate axis in Kelvin and time is plotted along the abscissa in seconds. A voltage is applied to the first carbon nanotube layer **302** at time t=0 (**402**). Prior to time t=0 seconds, no current is supplied and the first carbon nanotube layer **302** is at a room temperature, i.e., about 290 K. Supplying the electrical current at time t=0 (**402**) causes the temperature of the first carbon nanotube layer **302** to rise to an equilibrium temperature of about 550 K at about t=2 seconds (**404**).

In contrast, conventional blackbody sources require from several minutes to several hours to reach an equilibrium temperature. Additionally, due to the length of time required to bring the conventional blackbody sources to an equilibrium temperature, the conventional blackbody sources are generally maintained at or near their equilibrium temperatures when not in calibration mode in order to be substantially prepared when calibration is needed. Calibration systems that use conventional blackbody sources therefore consume a large amount of power. Since the thin film structures of the present disclosure are able to reach equilibrium temperatures in relatively short time (i.e., less than about 20 seconds), there is no need to maintain the thin film structure at the equilibrium temperature during non-calibration times. Additionally, the thin film structure may thus be used to calibrate the sensors within an acceptable time frame, such as in less than 20 seconds. It is to be appreciated, however, that use of the thin film structure need not be limited to operations in which an expected time frame for completing a relevant task is 20 seconds or less. Therefore, calibrating optical sensors using the exemplary thin film structure of the present disclosure may be used on-demand which can save greater than about 90% of the operational costs over calibration methods using conventional blackbody sources.

FIG. **5** shows a table illustrating a relation between current supplied to the exemplary carbon nanotube film **200** and equilibrium temperatures of the first carbon nanotube layer **302** of the thin film structure **200**. The first column indicates an amount of current (in Amps) applied to the first carbon nanotube layer **302**. The second column indicates a target temperature (in Kelvin) that is expected to be achieved when the selected current is applied. Columns 3, 4 and 5 show measured temperatures (in Kelvin) achieved when the selected voltage is applied to the first carbon nanotube layer **302** at times of 10 seconds, 60 seconds and 180 seconds, respectively. Spatial variations in temperature are also shown by the second number provided in each of Columns 3, 4 and 5 (i.e., "±1," "±6," etc.). The actual temperatures show relatively small spatial variation in temperature and are stable over the shown times (i.e., 10 seconds, 60 seconds and 180 seconds). Spreading the heat from the first carbon nanotube layer **302** through the first thermally conductive layer **304** reduces the spatial variation to within a selected range that is less than about 1.0 Kelvin, about 0.5 Kelvin or about 0.1 Kelvin, in various embodiments. Thus, the second carbon nanotube layer **306** is uniformly heated and each of the plurality of carbon nanotubes **312***a*-**312***m* emits a blackbody radiation spectrum corresponding to substantially the same temperature. Selecting the amount of current supplied to the first carbon nanotube layer **302** therefore substantially controls a blackbody radiation spectrum produced at the second carbon nanotube layer **306**. Thus, over a suitable calibration time frame, the thin film structure can be used to provide a substantially blackbody radiation spectrum suitable for use in calibrating a sensor. In alternative embodiments, the spreading of the heat from the first carbon nanotube layer **302** through the first thermally conductive layer **304** can be used to reduce the spatial variation to within a range of about 2 Kelvin or about 3 Kelvin. It is to be appreciated that the thin film structure can be used to reduce the spatial variation of temperature to within about 1.0 Kelvin even in operations in which such reduction in spatial variation of temperature is not needed.

Due to the relatively quick response of the thin film structure to the applied power, the blackbody radiation spectrum provide by the calibration apparatus **106** may be altered in a relatively quick amount of time. Therefore, the calibration apparatus **106** may be used to quickly provide multiple blackbody radiation spectra to the sensor.

In an exemplary calibration process, a first voltage is sent through the first carbon nanotube layer **302** of the thin film structure **200** of the calibration apparatus **106** to generate a first set of photons of a first blackbody radiation spectrum. The sensor **102** is then calibrated to a first photon flux from the first blackbody radiation spectrum at a selected calibration wavelength, i.e., over a wavelength window corresponding to the selected calibration wavelength. Subsequently, a second voltage is sent through the thin film structure **200** to generate a second set of photons of a second blackbody radiation spectrum. The sensor **102** is then calibrated to the second photon flux from the second blackbody radiation spectrum at the selected calibration wavelength. This process may be repeated any number of times using the same thin film structure **200** to calibrate the sensor **102** at any number of photon fluxes at selected wavelengths before completing the calibration process. In alternate embodiments, a plurality of calibration wavelengths is used, and the plurality of photon fluxes is measured at each of the plurality of calibration wavelengths to calibrate the sensor. At the end of the calibration process, the calibration apparatus **106** is moved or rotated out of the optical path **104** of the sensor **102** so that the sensor **102** can be used for its intended purpose. The ability of the thin film structure **200** to provide multiple calibration wavelengths enables a smaller and lighter calibration apparatus design than known calibration apparatuses that use multiple conventional blackbody radiation sources.

FIG. **6** shows a cross-sectional view of the thin film structure **200** of the present disclosure in an alternate embodiment. The thin-film structure **200** includes a first layer (referred to herein as a "first carbon nanotube layer **602**") in electrical contact with electrodes **604***a* and **604***b*. The electrodes **604***a*, **604***b* may be connected to a power supply (not shown) in order to supply a current through the first carbon nanotube layer **602**. A top side of the thin-film structure **200** and a bottom side of the thin-film device **200** are labelled in FIG. **6** for illustrative and explanatory purposes. The top side is generally in a positive z-direction as indicated by the coordinate system **625**. The first carbon nanotube layer **602**, as well as the other layers of the thin-film device **200**, is considered to lie in the x-y plane of the coordinate system **625**. The first carbon nanotube layer **602** includes carbon nanotubes that are oriented in the plane of the first carbon nanotube layer **602**. When voltage is applied to the first carbon nanotube layer **602**, heat is generated which flows out of either a top face **602***a* of the first carbon nanotube layer **602** or a bottom face **602***b* of the first carbon nanotube layer **602**. Thermal spreading layer **606** is disposed on the top face **602***a* of the first carbon nanotube layer **602**. A second carbon nanotube layer **608** (referred to herein as a "second carbon nanotube layer **608**") is adjoined to the thermal spreading layer **606** so that the thermal spreading layer **606** is sandwiched between the first carbon nanotube layer **602** and the second carbon nanotube layer **608**. The second carbon nanotube layer **608** includes a planar surface **614** that are aligned in the x-y plane and a plurality of carbon nanotubes **616** attached to a top of the planar surface **614** and aligned normal to the planar surface (i.e., with longitudinal axes of the plurality of carbon nanotubes **616** aligned in the z-direction). In one embodiment, the planar surface **614** is a layer of alumina substrate (Al_2O_3).

In operating the thin-film structure **200**, an applied voltage generates heat at the first carbon nanotube layer **602**. The heat is transmitted through the thermal spreading layer **606** to the second carbon nanotube layer **608**. At the second carbon nanotube layer **608**, the heat excites photons from the plurality of carbon nanotubes **616**, which photons are emitted in the positive z-direction. The emitted photons generate a blackbody radiation spectrum.

The spatial distribution of heat generated by the first carbon nanotube **602** tends to vary within the x-y plane. A function of the thermal spreading layer **606** is to reduce this variation of heat within the x-y plane by the time the heat reaches the second carbon nanotube layer **608** so that the temperature and thus the photon emitted flux is even across the surface of the second carbon nanotube layer **608**. The structure of the thermal spreading layer **606** is selected so as to achieve this reduction in spatial heat variation.

In particular, the thermal spreading layer **606** includes at least one graphene sheet for distributing heat emanating from the top face **602***a* of the first carbon nanotube layer **602**. The graphene sheet is a compressed layer of graphene platelets. The graphene sheet conducts heat with high efficiency. Thus, the graphene sheet is a highly thermally anisotropic, meaning that heat flows in a plane of the graphene sheet according to a first thermal conductivity and flows normal to the plane of the graphene sheet according to a second thermal conductivity that is much less than the first thermal conductivity. As a result of this thermal anisotropy, graphene is used to reduce any spatial variations in heat density in the plane of the graphene. Since the graphene sheet is aligned in the x-y plane, the variations are smoothed in the x-y plane.

In one embodiment, the thermal spreading layer **606** includes a single graphene sheet between the first carbon nanotube layer **602** and the second carbon nanotube layer **608**. In another embodiment, the thermal spreading layer **606** includes a stack of graphene sheets. In the illustrative embodiment of FIG. **6**, the stack includes at least a first graphene sheet **610***a* and a second graphene sheet **610***b*. The first graphene sheet **610***a* and the second graphene sheet **610***b* may be joined by an adhesive layer **612***a*. The adhesive layer **612***a* is thermally insulating, although not necessarily thermally anisotropic, and allows heat transfer between the first graphene sheet **610***a* and the second graphene sheet **610***b*. Additionally, an adhesive layer **612***b* may be disposed between the first carbon nanotube layer **602** and the first graphene sheet **612***a*, and an adhesive layer **612***c* may be disposed between the second carbon nanotube layer **602** and the second graphene sheet **612***b*. The adhesive layers **612***b* and **621***c* may similarly be thermally insulating as, although not necessarily thermally anisotropic. As heat propagates away from the top face **602***a* of the first carbon nanotube layer **602**, the heat is distributed throughout the first graphene sheet **610***a* in the x-y plane. The heat is then directed from the first graphene sheet **610***a* to the second graphene sheet **610***b*. The second graphene sheet **610***b* further distributes the heat in the x-y plane. Thus both the first graphene sheet **601***a* and the second graphene sheet **601***b* are employed in reducing spatial variation of heat in the x-y plane. While two graphene sheets are shown in FIG. **6**, it is to be understood that any number of graphene sheets may be used in the thermal spreading layer **606** in other embodiments. The use of multiple graphene sheets helps to reduce the non-uniformity in the spatial variation of heat in the x-y plane.

The thin-film structure **200** further includes a reflector **620** disposed on the bottom face **602***b* of the first carbon nanotube layer **602**. The reflector **620** directs heat emanating from the bottom face **602***b* back in the direction of the first carbon nanotube layer **602**. The reflected heat thus passes through the thermal spreading layer **606** and is used to excite photons at the second carbon nanotube layer **608**. In one embodiment, a graphene sheet **622** and adhesive layer **624** may be disposed between the first carbon nanotube layer **602** and the reflector **624**. Thus, the reflected heat is spatially distributed by the graphene sheet **622**.

The thin-film structure **200** of FIG. **6** is light weight, typically less than about 40 grams and has a thickness of about 25 mils (0.635 millimeters). Therefore, the thin-film structure may be used in various operations or equipment in which space is restricted and/or in which equipment weight is of concern. The temperature variation of the energy emitted from the top surface of the second carbon nanotube layer **608** is less than about 0.05 K across the surface of the second carbon nanotube layer **608**.

The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the invention. As used herein, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms "comprises" and/or "comprising," when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one more other features, integers, steps, operations, element components, and/or groups thereof.

The corresponding structures, materials, acts, and equivalents of all means or step plus function elements in the claims below are intended to include any structure, material, or act for performing the function in combination with other claimed elements as specifically claimed. The description of the present invention has been presented for purposes of illustration and description, but is not intended to be exhaustive or limited to the invention in the form disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art without departing from the scope and spirit of the invention. The embodiment was chosen and described in order to best explain the principles of the invention and the practical application, and to enable others of ordinary skill in the art to understand the invention for exemplary embodiments with various modifications as are suited to the particular use contemplated

The flow diagrams depicted herein are just one example. There may be many variations to this diagram or the steps (or operations) described therein without departing from the spirit of the invention. For instance, the steps may be performed in a differing order or steps may be added, deleted or modified. All of these variations are considered a part of the claimed invention.

While the exemplary embodiment to the invention had been described, it will be understood that those skilled in the art, both now and in the future, may make various improvements and enhancements which fall within the scope of the claims which follow. These claims should be construed to maintain the proper protection for the invention first described.

What is claimed is:

1. An apparatus for producing a blackbody spectrum, comprising:

a first carbon nanotube layer configured to generate heat in response to an applied voltage;

a second carbon nanotube layer configured to emit the blackbody radiation spectrum in response to the heat from the first carbon nanotube layer; and

a thermal spreading layer between the first carbon nanotube layer and the second carbon nanotube layer, the thermal spreading layer including a graphene sheet configured to reduce a spatial variation of the heat in a plane of the thermal spreading layer.

2. The apparatus of claim **1**, wherein the first carbon nanotube layer includes carbon nanotubes aligned in a plane of the first carbon nanotube layer.

3. The apparatus of claim **1**, wherein the second carbon nanotube layer includes a planar surface and a plurality of carbon nanotubes, wherein a selected carbon nanotube has a longitudinal axis directed substantially normal to the planar surface and emits photons directed along the longitudinal axis in response to the heat from the first carbon nanotube layer.

4. The apparatus of claim **1**, wherein the graphene sheet further comprises a graphene stack having at least a first graphene sheet and a second graphene sheet.

5. The apparatus of claim **4**, further comprising a thermally insulating adhesive layer between the first graphene sheet and the second graphene sheet.

6. The apparatus of claim **1**, further comprising a controllable power supply configured to apply the voltage to the first carbon nanotube layer.

7. The apparatus of claim **6**, wherein a characteristic wavelength of the blackbody radiation spectrum is related to a magnitude of the applied voltage at the first carbon nanotube layer.

8. The apparatus of claim **1**, further comprising a reflective layer disposed on a side of the first carbon nanotube layer opposite the thermal spreading layer.

9. The apparatus of claim **8**, further comprising a graphene sheet disposed between the first carbon nanotube layer and the reflective layer.

10. A film structure for generating a blackbody radiation spectrum, comprising:

a first carbon nanotube layer configured to generate heat in response to an applied voltage;

a second carbon nanotube layer configured to emit the blackbody radiation spectrum in response to the heat from the first carbon nanotube layer; and

a thermal spreading layer between the first carbon nanotube layer and the second carbon nanotube layer, the thermal spreading layer including a graphene sheet configured to reduce a spatial variation of the heat in a plane of the thermal spreading layer.

11. The film structure of claim **10**, wherein the second carbon nanotube layer includes a planar surface and a plurality of carbon nanotubes, wherein a selected carbon nanotube has a longitudinal axis directed substantially normal to the planar surface and emits photons directed along the longitudinal axis in response to the heat from the first carbon nanotube layer.

12. The film structure of claim **10**, wherein the graphene sheet further comprises a graphene stack having at least a first graphene sheet and a second graphene sheet.

13. The film structure of claim **12** further comprising a thermally insulating adhesive layer between the first graphene sheet and the second graphene sheet.

14. The film structure of claim **10**, further comprising a thermally insulating adhesive layer disposed between the graphene sheet and the second carbon nanotube layer.

15. The film structure of claim **10**, further comprising a reflective layer disposed on a side of the first carbon nanotube layer opposite the thermal spreading layer.

16. A method of producing a blackbody radiation spectrum, comprising:

applying a voltage to a first carbon nanotube layer of a thin film device in order to generate heat at the first carbon nanotube layer, wherein the thin film device includes the first carbon nanotube layer, a second carbon nanotube layer and at least one graphene sheet disposed between the first carbon nanotube layer and the second carbon nanotube layer; and

using the at least one graphene sheet to reduce a spatial variation of the heat in the plane of the thin film device, wherein the heat having the reduced spatial variation excites photons at the second carbon nanotube layer to produce the blackbody radiation spectrum.

17. The method of claim **16**, wherein exciting photons at the second carbon nanotube layer further exciting a plurality of carbon nanotubes, wherein a selected carbon nanotube has a longitudinal axis directed substantially normal to a planar surface and emits photons directed along the longitudinal axis in response to the heat.

18. The method of claim **16**, wherein the graphene sheet further comprises at least a first graphene sheet, a second graphene and a thermally insulating adhesive layer between the first graphene sheet and the second graphene sheet.

19. The method of claim **16**, further comprising varying a magnitude of the applied voltage to select a characteristic wavelength of the blackbody radiation spectrum.

20. The method of claim **16**, further comprising using a reflective layer of the thin film device to reflect heat from the first carbon nanotube layer into the graphene sheet.

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